

Surface Systems R&D in NASA's Planetary Exploration Program*

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Abstract

In the last several years, since the successful 1997 deployment and operation of the Sojourner rover on the surface of Mars, NASA has entered a new era of space exploration, where the emphasis is on in-situ exploration of planetary surfaces by means of a new class of robotic systems. For example, advanced sample return rovers with demonstrated technology far beyond Sojourner are in preparation for Mars sample return missions within the next decade. In response to challenges in the more distant horizon, robots capable of autonomous reconfiguration for all terrain navigation, and for multi-robot cooperative operations within robotic outposts, are R & D topics of intense interest. Robotic outposts are relatively new mission concepts that aim to establish a permanent robotic presence on planetary surfaces, to conduct extensive science operations using multiple surface robots, and to pave the way for eventual human presence by the robotic deployment and assembly of the infrastructure necessary for subsequent human missions. They include also "sensor-web" technology investigations that are concurrently applicable to exploring our own planet and other planetary surfaces. Another important R & D topic is that of deep drilling using robots. The goal of this research is to demonstrate technology to search the Mars sub-surface for water and signs of past life, using autonomous robotic systems that can penetrate 10's and even 100's of meters below the surface. Other important applications of this drilling technology occur for mission concepts under development to acquire and return samples from asteroid and comet surfaces and sub-surfaces. In addition to mobility and access, technologies for scientific sample handling, packaging and curation, high reliability long-life surface systems for use in wide temperatures ranges, and astronaut/robot interactions are explored and developed. This paper presents an overview of the robotic surface systems research being supported by NASA, including investigations at universities, NASA centers, and other major centers for robotics research. The paper includes the results of terrestrial demonstrations that have been conducted to establish technology readiness for currently planned missions, as well as developments under way for more futuristic missions to be implemented later in the next decade.

*R & D supported by the Surface Systems Thrust Area within the NASA Cross-Enterprise Technology Development Program (CETDP). C. R. Weisbin manages this Thrust Area and is also Deputy Manager for the CETDP program.

1. INTRODUCTION

This paper reports on activities being supported by the Surface Systems Thrust of the NASA Cross Enterprise Technology Development Program, a research program within the NASA Office of Space Science. Surface Systems R & D supports development of technology for safe, self-sufficient and self-sustaining human presence beyond Earth. The research leads to cheaper, more efficient, and more productive exploration of planetary and other body surfaces in the solar system by means of autonomous robotic systems and hybrid human/robot systems. One of the primary responsibilities is to meet and even exceed the cutting edge technology needs of the customer enterprises [1] of Space Science, Earth Science, and the Human Exploration and Development of Space (HEDS).

Relevance to NASA Enterprises

The R & D relevance to these Enterprises can be summarized as follows. Planetary rovers are essential to survey unexplored terrain, locate and retrieve samples of interest, and place and deploy scientific instruments at specified locations. Robotic drills, sub-surface explorers, and mini-coring devices are needed to conduct sub-surface exploration at ever increasing depths. In the extreme of sub-surface exploration are ice penetrators for postulated Europa sub-sea exploration. Robotic anchoring and sampling systems are needed for mission to asteroids and comets. Sensor webs are arrays of possibly mobile surface and sub-surface sensors that are deployed for collection of spatially distributed data, and analysis of characteristics of entire regions. They have concurrent applications for Earth Science, in addition to being necessary for Space Science exploration of large regions on

planetary surfaces and sub-surfaces. Applications to the HEDS enterprise include robots for deployment of surface system infrastructures for power and habitat, and to provide assistance to humans in conducting complex surface operations.

The surface systems R & D develops the ability to move around within a planetary environment in order to make breakthrough scientific measurements on the surface, beneath the surface, as well as deployment of surface assets from flying platforms. One of the central objectives is to develop technology for mobility, which implies a combination of surface and sub-surface vehicles. The diversity of planetary environments to be explored requires more than one type of mobile platforms [2]. Important challenges for surface systems research are severe environments in temperature variations, long-operating lifetime, long range navigation in possibly rough terrain, and communications with Earth from relatively small vehicles as well as inter-vehicle communications among surface robots. Safe landing, deployment, and autonomous science operations are additional challenges.

Mobility Technology Goals

These challenges can be appreciated with a brief review of the currently set mobility requirements. Surface access in local areas measured in terms of < 1 km are anticipated for missions in the near future. This will lead to regional survey missions requiring rover traverses of < 1000 km, with the ultimate goal being global surface exploration with traverses of 1000 km and more. Subsurface access is beginning with relatively low-depth capabilities measured in terms of a few meters, leading to < 100 m capabilities for stratigraphic missions and reaching ice. The ultimate goal is to reach postulated reservoirs of liquid water at > 100 m.

Other Technology Goals

In addition to mobility and access, technologies for scientific sample handling, packaging and curation, high reliability long-life surface systems for use in wide temperatures ranges, and astronaut/robot interactions are explored and developed. Investment in research and technology in robotic systems for planetary exploration, cooperative robotic outposts, and deep drilling on planetary surfaces remain topics

of sustained interest, as well as "sensor-web" technology investigations that are concurrently applicable to exploring our own planet and other planetary surfaces.

Recent Success Story

Recent success stories include robotics technologies in mobility and navigation that made possible the Sojourner rover that roamed the surface of Mars in the summer of 1997, and that are under further development for planned sample return missions over the next decade. Its key technologies included autonomous hazard avoidance and navigation, a 6-wheeled rocker-bogie mechanism, autonomous deployment of an spectrometer instrument. This rover demonstrated that very useful science could be done with a miniaturized rover. The vehicle achieved a total traverse of about 100 meters, obtained about 15 spectrometer measurements of rocks in the vicinity of the lander, and obtained about 20 soil mechanics measurements. The deployment maneuver from the lander, which had to be done very carefully because of occlusions due to the balloon-like material from the landing system, was a challenge to mission operations. These capabilities establish a baseline for the technology under development in the Surface Systems Thrust. The objective of this research is to use the Sojourner experience as a point of departure to achieve unprecedented capabilities in several theme areas.

Structure of Surface Systems Thrust Activities

The thrust activities are subdivided into the following major theme areas: High Risk Access Systems, Robotics Outposts and Colonies, Deep Subsurface Systems, In-Situ Resource Utilization Systems, Sample Acquisition and Curation, Hybrid Human & Robot Systems, and University Collaboration. The remainder of the paper summarizes technological forecasts for each of these theme areas, as well as research tasks that are currently on-going.

2. HIGH RISK ACCESS SYSTEMS

This theme area develops smarter, faster, and more maneuverable rovers and other types of robotic surface systems. This includes unique mobility robotic mechanisms to do such risky tasks as descending cliffs and craters, as well as

multi-mode hybrid aerial/surface systems to provide wide area coverage and traverse extremely rugged territory.

- **Now** – Wheeled Rovers 100's meters; supervised autonomy; conventional terrain
- **5 yrs** – Multi-mode mobility (hop, fly, etc.); >100 km regional autonomy; all terrain capability; cliff ascent & descent
- **10 yrs** – > 1000 km multi-mode mobility surface coverage; coordinated communications; unattended autonomy
- **>15 yrs** – High-resolution global surface coverage; precision assess & in-situ probe

2.1 Inflatable Technology for Robotics

The inflatable rover uses novel, large inflatable wheels to climb over rocks instead of traveling around them, thus enabling the rover to traverse quickly over 99% of the Martian surface. Preliminary tests using commercial nylon balloons as tires, a rigid metal chassis, and a simple, joystick control, have shown great promise.

We are developing more rugged, lightweight inflatable wheels and an inflatable and extendable chassis. This will confirm the ability to pack the rover into a small planetary entry capsule. We are also incorporating an autonomous control system that allows the rover to follow an astronaut or to uniquely climb over most obstacles to designated sites in a Mars-like terrain, while carrying smaller, conventional rovers in cooperative rover studies.



Fig. 1 Inflatable Rover Technology

This inflatable rover technology constitutes a paradigm shift from small rovers, because a small rover is being built that inflates its tires, spokes, and chassis, and grows into a "Monster

Truck" which can scale most of the obstacles that it encounters.

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2.2 Nanorover Outposts

Previous research in miniaturized rover technology has led to the MUSES-CN flight experiment to be launched in 2002 for an asteroid surface exploration mission. This experiment will fly has a single flight-qualified vehicle, less than 1kg in mass. The rover has advanced mobility consisting of 4-wheels, self-righting, and with active articulation.



Fig. 2. Nanorover Technology

This is combined with advanced sensing consisting of capacitive proximity sensing on each wheel and accurate laser ranging to 10 meters. The vehicle has advanced cryovac microactuators for operation at 100K to 400K, and advanced chip-on-board wide-temperature electronic packaging of a 32-bit flight computer with a custom flight I/O gate array. This foundation is being used to develop a prototypical example of a robotic outpost system that performs a useful function at Mars or other planetary surfaces.

The mission concept to be developed is to have a solar concentrator deployed from a mast that concentrates sunlight onto a small region of the ground. A group of solar powered rovers gather at this site and use percussive devices to excavate terrain material. The solar panels on the back of each nanorover pop up into a "dump truck" configuration, where the excavated terrain can be put for transport. The excavation can be

an open trench or a tunnel whose walls can be lined with reflective foil to keep the intense solar power available all the way to the end of the tunnel where the excavation occurs. This multitude of small rovers with percussive rock breaking devices, together with the solar concentrator tower, has been dubbed "Snow White and the 700 Dwarves". The objective of the task is to explore the scaling relations and distributed control methodology needed to achieve this objective.

Brian.H.Wilcox@jpl.nasa.gov of the NASA Jet Propulsion Laboratory is the principal investigator.

2.3 Robust Task Execution for Robotic Exploration of Planetary Surfaces

Plans for future exploration of planetary surfaces require robotic agents capable of executing sequences of complex tasks with little or no human supervision. These robotic agents must use onboard software to select actions to achieve high level tasks designated by mission controllers. Developing an onboard software architecture for robust task execution is crucial to the success of future planetary surface exploration missions.

We are investigating the use of reinforcement learning methods to develop a robust, fault-tolerant task execution software architecture for surface exploration robots. Experimental evaluation of the approach will be verified initially using a rover-terrain simulator developed at NASA Ames Research Center with final verification using a hardware prototype rover in a variety of terrain types.

John.Loch@arc.nasa.gov of the NASA Ames Research Center is the principal investigator.

2.4 Accurate Positioning In Natural Terrain

The objective of this task is to enable rovers to navigate reliably for extended missions in harsh terrain. The rover-positioning problem decomposes into three complementary research areas, based on the required accuracy and natural reference frames for specifying rover commands.

These three areas are (1) coarse absolute positioning, over a wide area during long traverses between science sites; (2) fine absolute positioning within the small area of a science

site; and (3) precise relative positioning between the rover and a science target feature for terminal maneuvers and instrument placement.

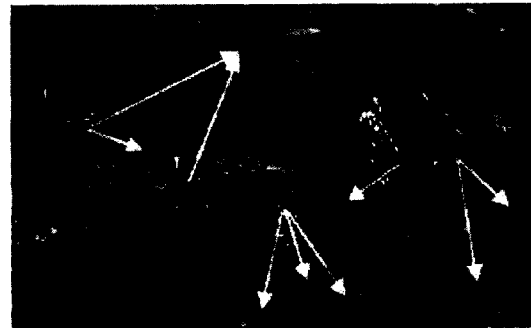


Fig. 3 Natural Landmark Identification

The goal of this task is to develop a competent navigational solution by combining natural landmark identification and tracking and pseudolite GPS for absolute positioning, and visual servoing for relative positioning and terminal maneuvers. These methods provide continuous, low latency feedback on rover motion, with minimal on-board hardware resources

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2.5 Reconfigurable Robotic Surface System for All Terrain Exploration

We are creating a novel reconfigurable robotic surface system enabling access and in situ science at high value, high-risk planetary locations such as escarpments, fissures, or breakout channels.

The technology concept is a modular system, as configured from a reusable, fixed parts inventory. The system can autonomously change shape, mechanical functions, and control actions in response to sensed internal state or external observations. Criteria for success are system ability to self-adapt to changing terrain characteristics, achieve high terrainability relative to mass-scale, and at the extreme, discretely reconfigure its functions to escape/recover from entrapment or other major operational anomalies. R2S2 has a further powerful property of being physically separable into two (or more) cooperating agents during use--allowing extended baseline observations, networked instrument activities, or even

coordinated robotic work (e.g., one robotic agent anchors; the other rappels).

Many different initial system configurations are possible, based on the target task. This "reusable" combinatorial design and fixed inventory greatly benefits mission cost, launch access, and survivability, and has broad application to robotic outposts. Technical products include a virtual prototyping environment (CMU), sensor-based autonomous control software (JPL/MIT), and task-level mobility synthesis and inventory optimization tools (UNL/MIT).

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2.6 Safe Navigation Of Planetary Rovers On Challenging Terrains

This work develops and validates the core technologies needed to enable planetary rovers to traverse long distances on challenging terrains safely and autonomously. New techniques will be developed for real-time terrain assessment by inferring physical properties of the terrain (such as slope, roughness, and hardness) from the measurements provided by on-board sensors.

Novel techniques for terrain-based rover navigation are developed in which the terrain quality data is used continuously in the rover navigation logic to guide the rover toward the safest and the most traversable terrain, while heading toward the designated goal and avoiding unexpected obstacles. Both terrain assessment and rover navigation are performed at multiple resolutions (global, regional, local) to maximize rover survival.



Fig. 4. Terrain Based Rover Navigation

Several field tests on representative natural terrain will be conducted for validation, and the sensing and navigation algorithms will be improved based on the experimental results obtained. The outcome of this research will significantly enhance rover safety and, in turn, allow successful completion of robotic exploratory missions in high-risk access terrain

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3. ROBOTIC OUTPOSTS & COLONIES

This theme area focuses on multiple cooperating robots forming autonomous robotic surface system colonies for in-situ surface measurement and communications and to pave the way for human exploration of planetary surfaces. It encompasses multi-robot control architectures for robot coordination, as well as self-sustaining robotic systems to achieve permanent and even perpetual presence by means of such technologies as autonomous robotic repair systems.

- **Now** - < 10 Sojourner-class rover surveys; local area in coordination with landers; daily Earth communications
- **5 yrs** - Low cost robot teams; wide area measurement & communication nets; weekly hands-off operations
- **10 yrs** - Self sustaining systems; robotic repair and maintenance; monthly hands-off operations; team work
- **15 yrs** - Permanent presence in deep space robotic infrastructures; long duration autonomy

To illustrate the challenges involved in developing robotic outposts, consider the key technological features needed:

- **Permanent Presence:** many year robot operation, requiring longer life and cheap and replaceable components and systems, and even more critically the capability for in-situ robotic repair of surface assets
- **Division of Robot Labor:** cooperative operation of resource suppliers, scouts,

drillers, workers, load-movers, smart leaders, etc.

- **Self-Sustainability:** robots and surface systems that balance energy use and generation, thrive on challenges, and have survival instinct.
- **Opportunistic Adaptation:** robots that create and capitalize on opportunities to do better things better.
- **Collective Autonomy:** groups of robots that do cooperative job with minimal ground intervention.
- **Ultra-Cumulative Efficiency:** ensembles of robots whose cumulative output is much greater than the sum of individual unit outputs.

3.1 Planetary Surface Robot Work Crews

We investigate previously unexplored and important problems in multi-robot coordination to do cooperative work in the moving and handling of objects on sloped and rocky planetary surfaces. New approaches are investigated in cooperative move and force control of mobile robots working together, cooperative teams of multiple robots of different types in tasks that no single robot can do by itself; and minimally intrusive control architecture concepts that optimize local autonomy and operator intervention.

This research supports a wide variety of surface operations that require moving of either human made or natural objects on planetary surfaces. These mission operations include deployment of solar panels and other large infrastructures; movement of rocks, containers and other small objects; deployment of multiple sensor arrays for measurement and observation; anchoring of deployed structures; and clearing of terrain.

The robot work crews could operate in a purely robotic mode, or they could be assist astronauts conducting extensive EVA operations. The research conducts scaled experiments motivated by space mission scenarios, and collects data with increasingly more complete scenarios.

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3.2 Robust, Hierarchical, Autonomous Task Planning for Robotic Colonies

This task develops an autonomous, robust, multi-robot, task planning management system to enable a large number of robotic vehicles to work cooperatively to accomplish a global goal that simultaneously responds autonomously to failures. It focuses on a fundamentally new level of planning not previously addressed, yet which represents a required capability for the successful operation of a colony of robots on Mars.

Our approach is to develop an autonomous task-planning system based on a model of human work-groups where tasks and the available resources are divided among the subordinates who can further subdivide them to their own subordinates, etc, down to the lowest layer which consists of actual robots. This research is a natural and fundamental extension of previous work done at the Stanford Aerospace Robotics Laboratory.

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3.3 Distributed, Multi-Robot Control Architecture for Autonomous Construction Tasks

Multiple autonomous robots work close together to perform construction tasks. They share sensory data and synchronize task execution. They also accept input from humans and work with humans to perform complicated tasks.



Fig. 5 Distributed Multirobot Control Testbed

Current robot architectures usually focus on single robots or highly distributed multiple robots. These architectures also focus exclusively on autonomous robots and often do not provide mechanisms for human interaction. This task builds mechanisms that allow each robot to maintain its independence, yet still be part of a team effort, where the team members can be other robots or human crew. Quantitative experiments are performed at the NASA Johnson Space Center's Mobile Manipulation Testbed and at Carnegie Mellon University. The initial focus is on the basic algorithms of multi-robot cooperation between two robots and a human to assemble and deploy an antenna. Subsequent efforts will expand the range of tasks and the number of robots.

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4. DEEP SUBSURFACE SYSTEMS

This theme area develops techniques for subsurface sampling of planets and comets at tens of meters depth and more, including drills and moles as well as ice penetrating robotic probes.

- **Now** – 10's of samples in low-depth coring devices
- **5 yrs** - < 10 meters in Mars regolith by percussive robot systems; icy media robotic penetrator proof-of-principle experiments
- **10 yrs** - > 100 m access to samples in Mars regolith
- **15 yrs** – Active thermal probe for icy planetary environments

4.1 Active Thermal Probe for Icy Earth and Planetary Environments

These robotic systems will be relevant to scientific objectives in Earth paleocirculation and ice dynamics science, Europa ocean and ice in-situ exploration, Titan prebiotic exploration, and Mars exploration, climate history science, and exobiology science. The mix of strong Earth and planetary science interests is crucial in supplying testing opportunities at terrestrial sites for robotic systems to be used in planetary applications with costs shared among agencies and programs.

In the past ice vehicles have been attempted, e.g. the Philberth Probes of the 1960s, and they were

unsatisfactory. We are developing a complete change of principle through application of techniques from hot-water drilling as successfully developed over the past decade by the glaciology program at Caltech (Engelhardt and Kamb, 1997) as well as modern materials, fluidics, and performance-monitoring methods. Other technology assessment and development activities are ongoing in other methods of drilling, and this project is intended to be collaborative with those activities.

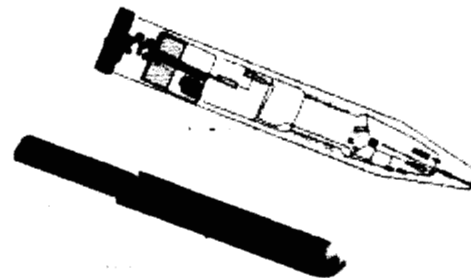


Fig. 6 Thermal Probes for Icy Environments

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4.2 Robotic Subsurface Explorer

The Robotic Subsurface Explorer (SSX) is a small, self-contained robotic device to penetrate significant distances underground, such as to explore below the permafrost layer on Mars into the liquid-water aquifer thought to be maintained by heat from radioactive decay within the planet and which may harbor extant life. The activity culminates in a penetration of many tens of meters (with a goal of a few kilometers) in the permafrost in the North Slope of Alaska, returning samples of the subsurface environment through a small capillary tube included in the tether.

The prototype vehicle is approximately 0.3 to 1.0 meter long, 3 cm in diameter and weighs 10 kg. It uses about 100 W of power, which is transmitted over a ~ 2 km fine-wire tether. The vehicle is capable of penetrating 10 m to 3 km, depending on the vehicle length and power. A highly efficient percussive mechanism converts > 70 % of tether power to hammer energy. Samples are returned to the surface over a 0.1 mm capillary. The sampling system uses liquid

CO₂ (Mars) or Argon (Comets) to return 0.1 mm particles to the surface lander.

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4.3 >100m Access into Mars Regolith

Research conducted during the last 10 years on earth has revealed that life can exist deep beneath the surface of a planet. The results of this deep subsurface research on earth combined with current data from Mars missions suggesting the presence of liquid water early in Mars' history and mathematical modeling of the fate of water on Mars suggest that liquid water may exist deep beneath the surface of Mars. The existence of liquid water deep beneath the Martian surface gives rise to the hypothesis that life may exist deep beneath the surface of Mars.

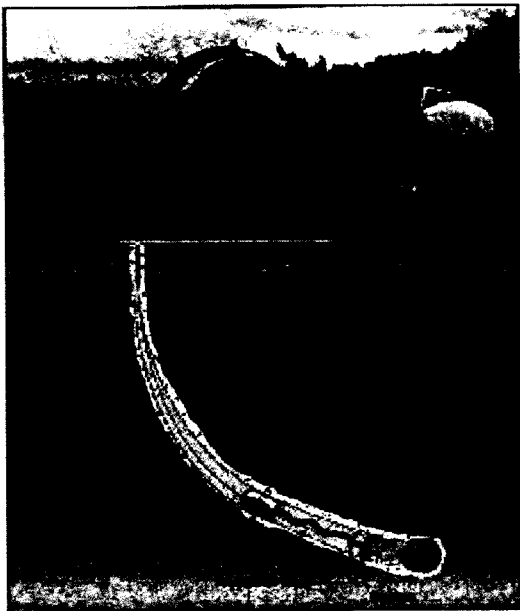


Fig. 7 Deep Subsurface Research

Based on the most current model of the physical state, depth, volatile content and history of the martian megaregolith (Clifford, 1993), it is plausible that deep hydrosphere will be discovered to underlie kilometers-thick, near-surface ground ice within the cryosphere (the region permanently below the freezing point of water). The purpose of this task is to explore various alternative techniques for collecting subsurface data, and to conduct proof of principle experiments.

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5. HYBRID HUMAN & ROBOT SYSTEMS

This theme area focuses on robotic assistance to surface EVA to do tasks that are more easily done by robots under supervisory human control; technology to allow humans and robots to work together in achieving complex (e.g. repair) tasks.

- **Now** – Rovers do full sample acquisition cycle with 1 ground command
- **5 yrs** – collective autonomy of < 10 robots commanded from Earth
- **10 yrs** – Remote robotic assistance to Earth based science analysis
- **15 yrs** – Robot crews help humans in surface science operations

5.1 Astronaut/Robot Interaction for Surface EVA Robotic Assistance

Plans for human exploration of Mars leverage robotic vehicles and information technology to multiply EVA crewmember efficiency during surface operations. A crewmember in a space suit faces a unique set of kinematic and kinesthetic constraints on interacting with robotic agents.

Developing effective astronaut and robot interaction is an important step toward achieving the potential of such technology. We seek to investigate what information needs to flow between the human and the robot, and how that information should be captured or presented.

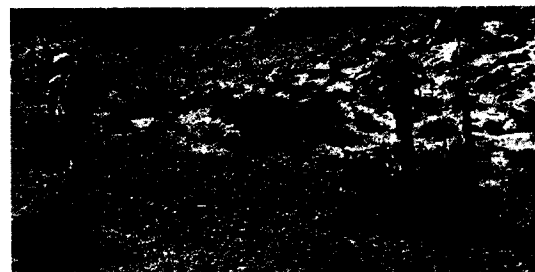


Fig. 8 Exploring a unique set of kinematic and kinesthetic constraints on interaction with robotic agents

We are primarily focusing on the case of an EVA crewmember accompanied by a small assistant

rover, but will also consider the interfaces for driving a rover. We are conducting field experiments each year to evaluate interaction technologies, individually and in combination, using suited test subjects in realistic terrain conditions.

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5.2 Multi-Resolution Mapping Using Surface, Descent, and Orbital Imagery

Our goal is to produce high accuracy maps of the terrain elevation and albedo at landing sites on planetary bodies through the use of all available imagery. Imagery is acquired during the lander descent to the surface, orbital cameras, and rover and lander cameras on the planetary surface. Techniques for three dimensional computer vision are used to analyze the imagery in order to generate dense terrain maps.

Map registration algorithms for the disparate types of imagery allow the relative positions of the maps to be determined and thus merged into an encompassing map. The data at the various resolutions is combined in a multi-resolution map structure to maintain efficient access and high resolution where available. This combination of information yields maps that can be used for rover navigation, scientific analysis, and potentially human exploration. Such maps allow rovers to travel in difficult terrain that cannot be traversed using current methods and provide a coordination mechanism for multi-vehicle systems, such as might occur in a robotic outpost

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6. SAMPLE ACQUISITION, HANDLING & CURATION SYSTEMS

This theme area develops techniques for in-situ handling and sample acquisition, sample storage and transport, and Earth returned sample curation and handling.

- **Now** – Small robot arms for surface handling
- **5 yrs** – automated extraction of volatiles from Mars regolith

- **10 yrs** – Multi-site land, ascent & sampling at 10's of sites
- **15 yrs** – Anchor, sample & retrieve robotic systems for irregular & poorly known media (asteroid & comets)

6.1 Innovative Curation and Handling Systems for Future Sample Return Missions

Samples returned from Mars or other solar system bodies with biological potential must be prevented from both contaminating the Earth and from being contaminated by the Earth. Furthermore, scientific value is greatly enhanced if returned samples are maintained at the conditions of the sampled body. This new effort is to develop systems for sample curation and handling in total isolation with capability for remote micromanipulation under cryogenic conditions.

The envisaged system is unique in that will combine a biosafety level 4 (BSL-4) environment with biogeochemical clean room and restricted materials requirements. When the system is required to operate at cryogenic conditions to simulated cold planetary environments, a flexible, dexterous, materials-restricted robot will be employed for sample preparation.



Fig. 9 Development of special handling for samples returned from other solar system bodies

Prior JSC experience and expertise in astromaterials curation and preparation of lunar samples is being used to define the requirements of the remote micromanipulator for use with Martian samples and samples from other future missions.

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6.2 Extraction of Volatiles (H, C, N, H₂O , etc.) from Lunar and Martian Regoliths

Systems for extracting volatile constituents (hydrogen, carbon, and nitrogen, water and helium) from regolith materials of the Moon and Mars are being defined, critical assumptions tested by experiment, prototype breadboard systems constructed, and possible space demonstration experiments defined.

Principal elements of the system are regolith mining and beneficiation; volatile, separation and purification; conditioning and storage. Use of novel concepts for material mining and transport, fiber optic systems for heating fluidized beds, and membrane technologies for gas purification can reduce mass and power for the system. The performance goal is to demonstrate a mass payback ratio (mass of useful product produced per year/mass of installed system) of 10 or greater.

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7. IN-SITU RESOURCE UTILIZATION SYSTEMS

This theme area develops surface systems that use in-situ resources, and balance their energy usage and generation, in order to achieve mission goals with minimal transport of energy and other resources from Earth. These surface systems enable science and human missions not possible without ISRU (e.g. hoppers, pneumatic equipment, long term science gases, etc.)

- **Now** – Mars propellant production breadboards and precursor experiments
- **5 yrs** – Base technology for Mars in-situ propellant production (ISPP) experiments
- **10 yrs** – ISPP fueled vehicles; micro-g soil processing and collection; subsurface resource collection & processing
- **15 yrs** – ISPP based robotic and human outposts

7.1 ISRU System Miniaturization

In-Situ Resource Utilization (ISRU) Systems require a number of integrated processes to acquire and convert local resources into usable products. Minimizing the mass, power, and volume associated with ISRU systems is critical for incorporation into both robotic and human exploration missions.

This work focuses on process intensification and system miniaturization by researching and testing concepts in the following areas first separately and then as an integrated system: 1) atmospheric gas collection & conditioning, 2) chemical reactors and heat exchangers, 3) reagent/product separation 4) water electrolysis, 5) micro valves and flow control devices and 6) micro sensors for process monitoring.

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8. UNIVERSITY COLLABORATION

This area summarizes major collaborative efforts with CMU, Stanford and MIT.

8.1 Robotic Search for Antarctic Meteorite Demonstration (CMU)

The primary goal of this task is to enable autonomous discovery of Antarctic meteorites using robotic search and automatic classification. The theme of the task provides an ideal format for demonstration of robotics in an environment and operational scenario analogous to exploration of the lunar and martian poles.



Fig. 10 Nomad - Antarctic Meteorite Search

The effort supports planetary science through the discovery of new meteorite samples, which provide the only significant source of geological material from outer space. Moreover, it augments the human search for Antarctic meteorites through thorough area searches and in-situ sample classification. Using a winterized Nomad robot this task has demonstrated the feasibility of automatic rock and meteorite classification from multiple sensors and autonomous navigation in polar terrain. The primary technical objectives for FY00 are integration of all autonomous capabilities into science autonomy - an architecture for intelligent exploration, automatic classification of samples, and coordination of mobility and manipulation for precise instrument placement - and demonstration of an autonomous search for new meteorites in Antarctica.

Dimi Apostolopoulos, dalv@ri.cmu.edu of Carnegie Mellon University, is the principal investigator.

8.2 Autonomous Rover Technologies (CMU)

This effort advances the robotic capabilities of planetary rovers through the creation and validation of mechatronic, perception, and cognition technologies. This research pursues breakthroughs and insights into aspects of robotic navigation, planning, and learning for autonomous exploration, precision positioning from tracking natural features, robust radar perception for mapping and safeguarding, and synthesis of reconfigurable robotic mobility for challenging planetary terrains.

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8.3 Multiple Cooperating Rovers (Stanford)

This is a broad-based research program focused on generating Ph. D. students expert in robotic system technologies critical to future NASA missions and generating fundamental advances in those technology areas. The objective of this research is to enable human/robot teams, enabling remote semi-autonomous operation of highly capable robotic systems for space and planetary exploration, multiple, cooperating robots, and more exploration of general mission

concepts envisioned for future NASA applications.

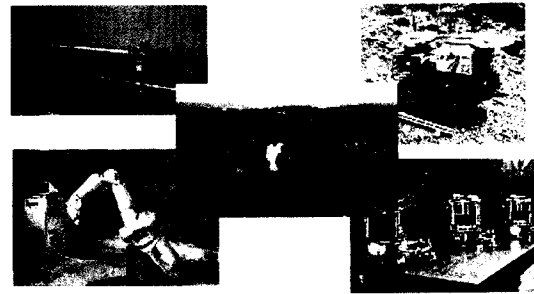


Fig. 11 Enabling Human/Robot Cooperating Teams

The underlying technologies in the robotic search demonstration are multi-sensor automatic classification with learning. The system architecture consists of interwoven sensing, driving and manipulation. The search architecture also enables information gain for sensing and planning.

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8.4 Physics-Based Rover Navigation and Sampling (MIT)

This task investigates motion control, planning, and manipulation techniques for robotic systems performing challenging tasks in rough terrain. This technology will allow robotic surface systems to access increasingly valuable science locations without compromising system safety.

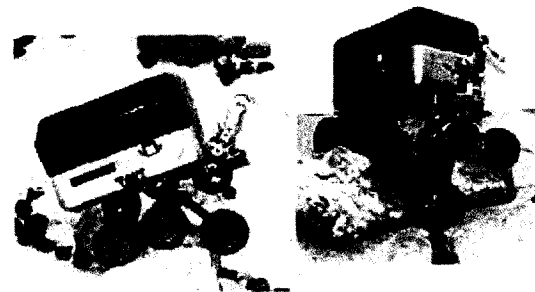


Fig. 11 Reconfigurable Mechanical Elements Employing "Smart" Materials

This study focuses on several areas. Mechanically reconfigurable rover systems will be studied, with a goal of developing systems which can autonomously change shape to optimize for a given task. Reconfigurable

mechanical elements that employ "smart" materials will be studied, as will algorithms for reconfiguration.

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9. CONCLUDING REMARKS

The surface systems technology under development has long range objectives that are quite challenging and will lead to revolutionary capabilities. Many of the technologies needing development are in their infancy.

- Multiple, coordinated multi-scale (small & large) special robots forming networks
- Remote robotic work systems (deploy habitats, drill, maintain other robots)
- Extend lifetime and power performance envelopes by orders of magnitude
- Local robotic outpost communication architectures and systems; high-rate surface switching & aggregation centers and/or aero-synchronous network relays
- Manufacture of propellants, oxygen, water, and other resources. However, substantial initial steps are being made toward the long range goals by seeking and supporting

activities which lead to early proof of principle experiments in selected areas. Evolution of the technology and infusion into flight systems will require major achievements from the community of researchers involved, and this effort will be quite interesting and exciting.

10. REFERENCES

- [1] <http://cetdp.jpl.nasa.gov/surface/ssys.html>
- [2] A Scientific Rationale for Mobility in Planetary Environments, Report of the Space Studies Board, National Research Council, 1998.

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